The Mission System Design Center: A Pilot of Formulation-Phase Concurrent Engineering in Aerospace Design

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Abstract. In this paper we describe pilots of a concurrent-engineering, formulation-phase design team demonstrated in spacecraft missions. This "Mission Team" operates within a design center called the Mission System Design Center, where design tools are linked via a central database and use large-screen projection systems to engage the entire team in system-level trade discussions. In these pilots, the Mission Team was able to manage complex trades, resolve conflicts, and rebalance requirements in the face of typical formulation phase issues. This team operates to periodically re-evaluate requirements and resource allocations (e. g., mass, power, funds, datarate) in the face of both externally and internally imposed changes.

INTRODUCTION

Engineering design practices are changing. They are changing because they can, and because they must. The capability to change gives designers freedom from many of the more pedantic elements of the job, such as data exchange challenges (data entry, file exchange, etc.), communications challenges (phone tag, meetings) and the like. The necessity to change stems from increasing pressure for efficiency.

Both designers and their managers vary in their response to changes in design practice, generally responding positively when the net effect is to increase percentage of time spent in the creative aspects of the task, but less so when there is uncertainty in the outcome. Managers seem especially wary of changes that might add risk to their program or that might not produce results as quickly or as well as existing practice.

In previous work we have described a formulation-phase design practice where teams work in concurrent engineering environments that remove the less creative elements and encourage participation by the entire team in resolution of problems. Use of team facilitation, automated data exchange mechanisms, interactive visualization, central database, and network-based distribution have been proposed as contributors to both increased creativity and efficiency. The present work describes two pilots that have been conduced to test those propositions and to gauge the acceptability of the new practice within the aerospace culture.

DESIGN METHODS

Phases of Design. In the civil space mission world, space missions are traditionally divided into four phases. The conceptual phase is dedicated to transforming an idea into a feasible design and a total cost accurate to perhaps +- 30%, usually for the purpose of assessing its marketability to some potential sponsor. The goals of this phase are (1) to determine if a feasible design exists; (2) to state the requirements on the development of the design and to develop at least a preliminary balance between them; (3) to estimate the total cost; and (4) to establish a realistic schedule by which the project could be executed.

Designs that are accepted pass into a second phase called formulation. The objective of this phase is to develop a buildable design based on requirements generated in the conceptual phase. In principle, these requirements are considered unchangeable, although in practice this is seldom the case for two reasons. First, deeper consideration of design almost invariably uncovers issues, some of which involve reconsideration at the system or even requirements level. Second, sponsor requirements, even at the highest level, frequently continue to change due to funds availability, changes in overall objective, or both. In mid-formulation phase a Preliminary Design Review (PDR) provides an opportunity to judge the solidity of the design, and a Critical Design Review (CDR) at the end of formulation phase proves the project ready to build hardware and software.

The implementation phase involves fabrication, purchasing, integration and test of the hardware and software necessary to accomplish the mission. Logically, this phase would involve no design, but both classes of exceptions noted above continue to exist in most cases. Finally, the operations phase begins with a launch of the spacecraft. Even here, however, design can continue to be necessary, as almost all spacecraft can be modified by command and/or onboard software updates. Mission alterations can still be needed as a result of either design flaws or sponsor initiative.

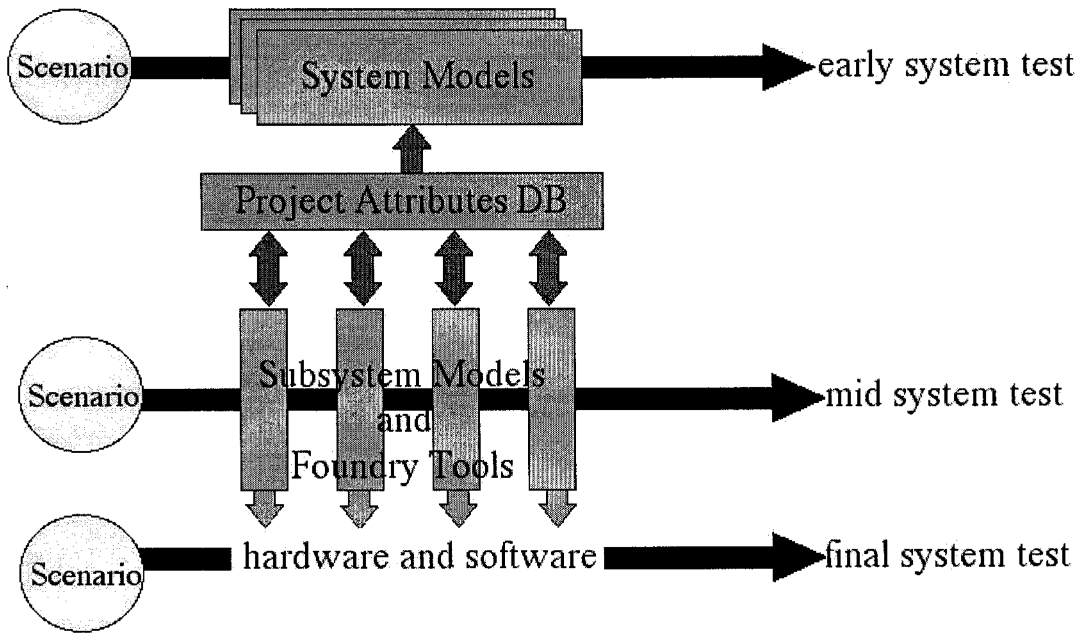

Figure 1. – Information Flow for the MSDC

Traditional Design Practice. Organization of the design process used over the past two decades has usually involved a unique team paced by periodically spaced meetings to report status, review action items, and establish new actions and deliverables. A dedicated, self-sufficient team designed each project from the ground up. Between meetings the design work was done largely by individuals working alone or in smaller groups. Periodic low-level reviews and design walkthroughs provided cross-fertilization among subsystems, and paper or other textural Interface Control Documents were written to define subsystem-to-subsystem interfaces. Major reviews, such as PDR or CDR, allowed extrernal reviewers to look for system-level inconsistencies.

Testing under this paradigm was done largely through such reviews and walkthroughs until something concrete existed to test in a more realistic way. Although in the past half-decade models of designs have come into existence, they have been used to test primarily at the subsystem level, or to model mission events such as entry, descent and landing. Integrated system testing has had to wait until physical hardware at final (or nearly so) software existed.

Traditional design practice has, of course, succeeded for years. However, it does not allow for validation of design until the design has been largely completed. It does not provide any forward indicator of success or failure. Although not widely practiced, model-driven design (e. g., Baker et al., 1997) promises to allow early detection of design errors, thus saving the time and money required when later discovery means significant amounts of rework .

THE MSDC CONCEPT

Teaming. Smith (1997) describes a teaming formulation on which the methodology described here is based. Three teams, the Mission Team, Design Team and Test Team act in parallel operation, interacting with a central database to efficiently pass design data between them. Details of an implementation of this concept are discussed by Wall (2000), and the overall information flow is shown in Figure 1. In brief, the Mission Team is responsible for creating and maintaining balance among requirements, the Design Team consists of individuals and (perhaps) subteams responsible for actually creating the subsystem designs, and the Test Team imports models of the design and later the produced hardware and software. When testing reveals discrepancies, these are first considered by the Design Team for resolution within the existing requirements allocated to subsystems. If resolution is not possible at this level, the discrepancies are relayed to the Mission Team to see if rebalancing of requirements will either resolve the issue or enable the Design Team to do so. The Mission Team is envisioned to consist of Design Team leaders, which encourages vertical communication, and the Mission Team's periodic sessions encourage horizontal communication.

Environment. We have implemented and are evaluating an environment in which the Mission Team would function (Figure 2). Called the Mission System Design Center, this room incorporates high-end design tools and a central database as described above. The area is designed to promote communication among a small team and visualization of all types of design issues. Five large projection screens are available to all workstations in several varieties of platforms. In particular, one screen permits large-scale visualization of structural issues and can accommodate small spacecraft at full scale. CAD visualization software can be used to see the structure at any available level of detail. Individual assemblies are directly linked via the project's Product Breakdown Structure to the Product Data Management System so that a single click leads to detailed drawings, status and other information.

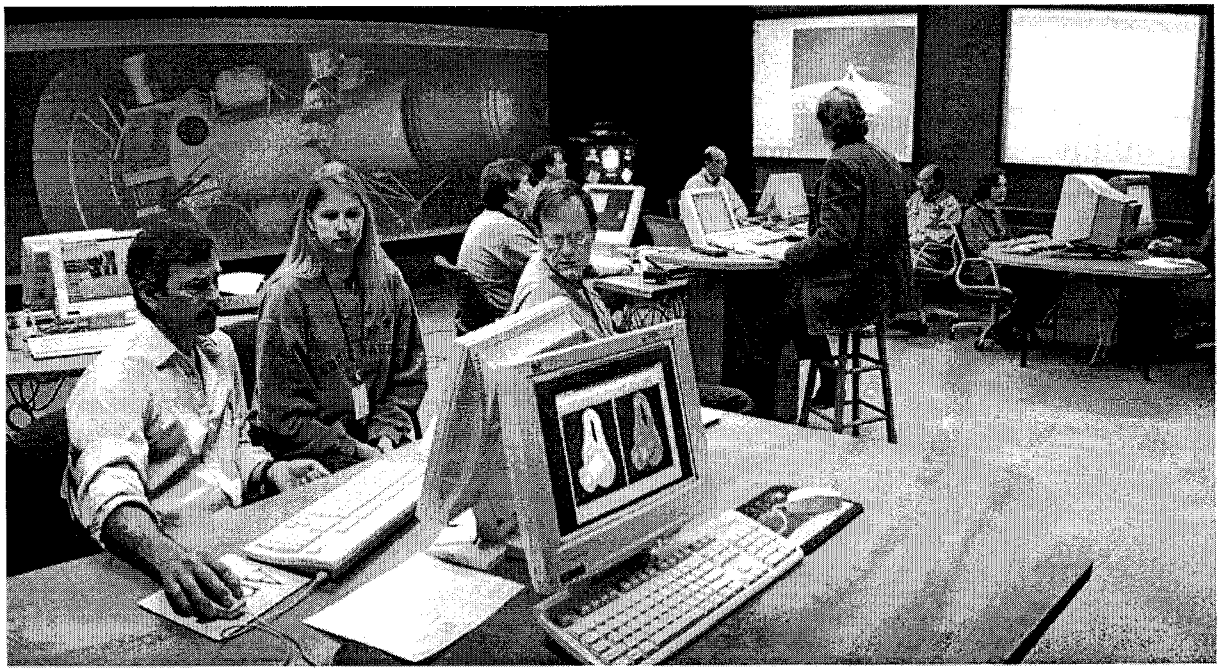

Figure 2.- The Mission System Design Center

Tools and Databases. A central database called the Product Attributes Database (PAD) connects to system level models (Barbieri and Estabrook, 1997) and acts as a repository for numerical descriptors of the design (Sercel et al., 1998). Design tools are linked into the PAD as well, so that changes to system parameters made in the PAD are immediately accessible and always current. The project's cost model takes values from the PAD to arrive at a parametric mission cost; likewise, schedule data can be (but in these pilots was not) stored in the PAD and retrieved for generation of schedules. Multiple layers of data in the PAD allow each parameter to be held "as allocated", "as estimated by subsystem", "as tested", etc., and also permits the keeping of multiple baselines.

Procedures. In this scheme, high-level mission goals (e.g., targets, data to be taken) are defined by the Mission Team, which includes such roles as the project scientist, mission engineer, and flight and ground system engineers. These are captured in a timelining tool. The team loads rough estimates of power, data and other resources for each event into this tool. Mission science teams and mission designers use this information to create a mission scenario that describes what activities the mission is to accomplish. The conceptual phase design is then used to create system requirements and a system design, which are stated in requirements modeling software as described in Wall et al. (1998). Parameters describing the design are stored in the PAD and linked to system models. A Product Breakdown Structure is created that attaches system level parameters (e.g., system mass, cost and power) to subsystem parameters (e.g., individual subsystem masses, costs and power). The system models are then executed using the timeline to ensure that the scenario can be executed by the designed system.

Imbalances at the system level can reoccur for several reasons. The mission sponsor sometimes directs the project to reduce costs or to readjust costs by year (cost profile). The science team may respond to recent scientific results or other needs by changing the scenario, or new findings about the mission environment (radiation levels, for example) may make the mission's task different in some way. Whereas past philosophy has been to resist such changes ("freeze the requirements"), experience has shown that they are common and maybe even inevitable. In our proposed scheme, at each rebalance by the Mission Team the latest updates from both system design and mission scenario are used, thus accommodating and evaluating changes to either. Similarly, management reviews are accomplished by witnessing the satisfaction of the scenario by the system models.

PILOTS

Piloting of potential changes to design practice at JPL has been used for several years as a part of the overall effort to update practice. Pilots involve the creation of a mock design effort, usually based on a current or recent real design, and a mock scenario. The purposes of pilots are (1) to demonstrate and allow an audience to evaluate the potential new scheme; (2) to force development of the necessary software, interfaces and environments to the point where they can be demonstrated; and (3) to educate designers on the new practice and receive their critique, especially with regard to the cultural acceptability of the change. The mock scenario sometimes predefines the design path so that interfaces and database population can be limited, and designers are sometimes allowed to prepare results ahead of time, but nonetheless pilots have been shown to be valuable ways of evaluating new process ideas.

Parameter	Issue
System Mass	60 kg over specification
Cost	Negative 6% margin against cost cap
Structure	Metal fatigue predicted by FEA
Mission	Additional data acquisition requirements imposed by sponsor
Data System	Insufficient onboard data storage

Table 1: Terrestrial Orbiter Pilot Issues

Terrestrial Orbiter Pilot. Two pilot exercises have been held to validate the Mission Team concept. For each, a Mission Team was assembled using experienced designers, a project manager, cost analyst and project scientist. A facilitator was used to keep order and to ensure that the new process was followed. In the first pilot, an Earth-orbiting spacecraft, in formulation-phase design, was assumed to face five typical issues (Table 1). The project manager requested the team to consider a smaller launch vehicle to recover cost margin, and a new baseline was created in the PAD for the design changes. The existing mass issue was of course made worse by the lower launch capacity. That problem was quickly assigned to a smaller group to work, and the assumed (fictional) structure contractor was contacted by telecon. In parallel, the facilitator addressed the additional data requirement and worked the requirements changes into the PAD. The timeline was modified in real time, and required onboard memory was revised, as determined by executing the requirements model. Sufficient memory was added and the necessary cost estimated. An online orbital analysis tool was used to add downlink stations as required. Next, the smaller team working the mass issue reported back to the larger group that a possible solution had been found using carbon composite material, but that additional funds were required. Structure design updates were made to the PAD directly from the contractor location. Cost savings due to the smaller launch vehicle almost but not quite balanced the added structure cost, and possible cost sharing with additional data customers was discussed. This potential rebalance of cost, mass and data was reduced to action items so that it could be re-reviewed at the next session.

Deep Space Pilot. To demonstrate the tools and data linkages required for missions with the more complex trajectories involved in extraterrestrial exploration missions, and to offer more broad exposure of the idea to designers, a second pilot was devised. In this case only one issue was initially presented, but several derived issues appeared as a result of the original proposed solution (Table 2). The target mission in this case was a reconnaissance survey of Jupiter's moon Europa.

In this pilot, the team reacted to the initial problem with a change in launch vehicle (as in the first pilot), but in this case the implication was a redesign of the cruise trajectory to decrease fuel mass. Solar electric propulsion was considered as an auxiliary propulsion system but was rejected because of the predicted cost and schedule impacts. Gravity assists were considered as another potential solution, but Earth swingbys were ruled out due to estimated costs of the related Environmental Impact Reports and related legal matters. Venus gravity assists were considered next, the impacts of the resulting arrival date delay assessed, and a potential thermal impact identified.

Via an automated transfer of the cruise trajectory to a thermal design tool, this impact was also assessed. Management concerns about such a seeming major change so close to PDR were put to rest by comparison of thermal maps of the spacecraft before and after some minor attitude, shielding and coating modifications. Second-order impacts of these changes, such as test chamber usage and deliver times were examined as well. CAD analysis, required to verify center-of-gravity impacts, was done quickly. Concerns about radiation damage to the onboard imaging system were raised, and a preliminary solution involving addition of shielding was devised. This in turn required another CG recalculation. A new baseline design was created in the PAD, although several action items were assigned to follow up with design teams on these preliminary decisions.

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Parameter	Issue
Schedule	Two weeks from PDR
Cost	Negative 2.2% margin against cost cap
Thermal (derived)	Predicted overheating due to new trajectory
Trajectory (derived)	Environmental Impact report and related effects of Earth swingby
Radiation dose/level (derived)	Effect on instrument due to new trajectory

Table 2: Deep Space Pilot Issues

RESULTS

Debriefs of both pilots were held with audiences and participants. Comments received were generally positive. Managers present at the first pilot estimated that issues of the complexity demonstrated might have taken several weeks to resolve using traditional practice. Some designers responded that the level of decisions made was probably too high, and that interaction with team members would be necessary before proposing solution, but that resulting action item followup might make such tentative decisions more acceptable. Other comments centered around cost of modeling software, reliability of model-based tests, and difficulty of dividing attention between multiple activities.

Cultural acceptability and ways of achieving it were also discussed. Most designers felt that the design center approach in general, and the MSDC concept in specific, would be accepted, although the level of intensity was questioned and the appropriate frequency for the Mission Team sessions was debated. Management audience members were divided in this discussion, some expressing surprise that the new process was not already in use, others concerned about being the first user of an unproven practice.

An unexpected result from the pilots was the communication that they inspired among designers. Needed interfaces were discovered during preparation, as for example the ability to transfer trajectory data from a trajectory design program into a thermal analysis program in the second pilot.

CONCLUSION

We have completed a prototype implementation of a concurrent-engineering based formulation phase design center, and we have created an accompanying design methodology. The methodology is based on the use of system models that allow system-level trades to be evaluated against mission scenarios, using the concept of executable specifications. A central database was used to hold system-level parameters describing the design, and changes to the design made during the sessions were made in that database and transferred in real time to design tools as necessary to follow the design as it evolved.

This implementation has been used in two pilots that together provided a fairly complete test of the method, with a set of typical formulation phase issues and mock design teams populated with experienced designers. Comments received were generally positive, with concerns expressed about intensity, level of decisions made and cultural acceptability.

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BIOGRAPHY